

Study of the $p\vec{d} \rightarrow n\{pp\}_s$ charge-exchange reaction using a polarised deuterium target

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Abstract

The vector and tensor analysing powers, A_y and A_{yy} , of the $p\vec{d} \rightarrow n\{pp\}_s$ charge-exchange reaction have been measured at a beam energy of 600 MeV at the COSY-ANKE facility by using an unpolarised proton beam incident on an internal storage cell target filled with polarised deuterium gas. The low energy recoiling protons were measured in a pair of silicon tracking telescopes placed on either side of the target. Putting a cut of 3 MeV on the diproton excitation energy ensured that the two protons were dominantly in the 1S_0 state, here denoted by $\{pp\}_s$. The polarisation of the deuterium gas was established through measurements in parallel of proton-deuteron elastic scattering. By analysing events where both protons entered the same telescope, the charge-exchange reaction was measured for momentum transfers $q \geq 160$ MeV/c. These data provide a good continuation of the earlier results at $q \leq 140$ MeV/c obtained with a polarised deuteron beam. They are also consistent with impulse approximation predictions with little sign evident for any modifications due to multiple scatterings.

Key words: Deuteron charge exchange, Polarisation effects

PACS: 13.75.-n, 25.45.De, 25.45.Kk

It was pointed out several years ago that the charge exchange of polarised deuterons on hydrogen, $\vec{d}p \rightarrow \{pp\}_s n$, can furnish useful information on the spin dependence

of elastic neutron-proton amplitudes near the backward centre-of-mass direction provided that the final proton pair $\{pp\}_s$ is detected at very low excitation energy E_{pp} [1]. In this limit the diproton is dominantly in the 1S_0 state and so there is then a spin-isospin flip from the $(S, T) = (1, 0)$ of the deuteron to the $(0, 1)$ of the diproton. At small momentum transfers between the deuteron and diproton, the

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deuteron charge-exchange amplitudes can be interpreted in impulse approximation in terms of np amplitudes times form factors that reflect the overlap of the deuteron bound-state and the diproton scattering-state wave functions [1].

Following pioneering experiments at Saclay [2,3], the most detailed studies of the $\vec{d}p \rightarrow \{pp\}_s n$ reaction were undertaken by the ANKE collaboration at deuteron energies of $T_d = 1.2, 1.6, 1.8$, and 2.27 GeV, i.e., at energies per nucleon of $T_N = 600, 800, 900$, and 1135 MeV [4,5]. At the three lower energies the predictions [6] of the impulse approximation model describe the data very well on the basis of np input taken from the SAID SP07 partial wave solution [7]. Deviations were, however, noted in the 2.27 GeV data [5] that were ascribed to an overestimate of the strength of the np spin-longitudinal amplitude at 1135 MeV.

The major constraint on the ANKE programme is the maximum deuteron energy of 2.3 GeV available at the COSY accelerator [8]. To continue the studies at COSY to higher energies, where there is great uncertainty in the neutron-proton amplitudes, the experiments have to be carried out in inverse kinematics, with a proton beam incident on a polarised deuterium target. The study of the charge exchange at low momentum transfers would then require the measurement of two low energy protons recoiling from the target [9]. We here report on the first measurement of the $p\vec{d} \rightarrow n\{pp\}_s$ charge-exchange at 600 MeV that extends the earlier deuteron beam data out to larger values of the momentum transfer q . Such a programme clearly first necessitates a reliable determination of the polarisation of the deuterium target and this will therefore be an important element of this letter.

The experiment was carried out using the ANKE magnetic spectrometer [10] situated inside the storage ring of the COoler SYnchrotron (COSY) [11] of the Forschungszentrum Jülich. The whole target facility consists of three major components: the atomic beam source (ABS) [12], the storage cell (SC) [13,14], and the Lamb-shift polarimeter (LSP) [15].

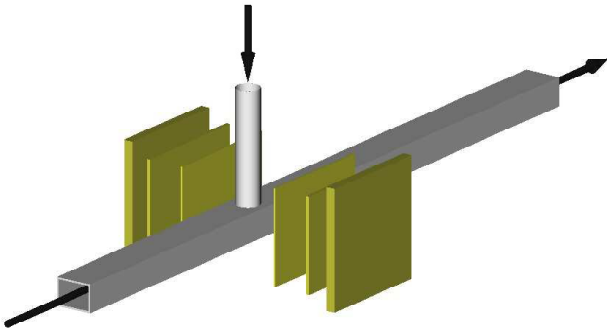


Fig. 1. Schematic view of the ANKE target area showing the positions of the polarised deuterium cell target and its feeding tube and the two Silicon Tracking Telescopes (STT). The beam direction is indicated by the long horizontal arrow.

The ABS is capable of providing deuterium beams with

different combinations of vector (Q_y) and tensor (Q_{yy}) polarisations. Four different modes were used in the current experiment with ideal polarisations of $(Q_y, Q_{yy}) = (+1, +1), (-1, +1), (0, -2)$ and $(0, +1)$, where the quantisation axis y is taken to be the upward normal to the plane of the COSY accelerator. The atomic beams from the ABS are led into the storage cell placed inside the ANKE vacuum chamber via a feeding tube and diffuse along the cell that is illustrated in Fig. 1. The Lamb-shift polarimeter, which measures the polarisation of the atomic beam from the ABS, is used for tuning the settings of the ABS before the experiments.

The polarised deuterium gas cell was rather similar to that used in the previous ANKE experiment with polarised hydrogen [5]. The cell was made of $25 \mu\text{m}$ thick aluminium foil (99.95% Al) with the inner walls coated with Teflon in order to minimise the depolarisation of the deuterium atoms. The cell had dimensions $20 \times 15 \times 390 \text{ mm}^3$ [13,14]. Such a cell increases the target thickness by about two orders of magnitude compared to using the ABS jet directly as a target and, as a result, an average luminosity of $L \approx 5 - 7 \times 10^{28} \text{ cm}^{-2} \text{ s}^{-1}$ was obtained over the ten days of data taking.

Though several nuclear reactions can be measured by detecting fast particles that pass through the ANKE magnetic analyser, both the polarimetry and the measurement of the charge exchange reaction were achieved by detecting only slow particles that emerge from the target cell using a pair of silicon tracking telescopes (STT) [16].

The two STT, each consisting of three double-sided silicon strip layers of $70 \mu\text{m}$, $300 \mu\text{m}$ and 5 mm thickness, were placed symmetrically inside the vacuum chamber, to the left and right of the cell, as shown in Fig. 1. The distances of the sensitive layers away from the target axis were 2.8 cm , 4.8 cm , and 6.1 cm so that the STT covered the laboratory polar angles $75^\circ < \theta_{\text{lab}} < 140^\circ$. In order to pass through the three layers, the recoiling protons or deuterons must have energies of at least 2.5 MeV , 6 MeV , and 30 MeV , respectively. For stopping particles the particle identification is unambiguous. In the case of proton-deuteron elastic scattering, which is the main polarimetry reaction used for this study, greater precision in the angle of the recoiling deuteron is achieved by deducing it from the energy measured in the telescope rather than from a direct angular measurement.

The experiment was conducted using the pairs of polarisation modes that are defined in Table 1. The ABS was configured in such a way as to provide identical polarised gas densities for the pairs of modes (1,2) and (3,4). The target was switched every 10 seconds, first between polarisation modes 1 and 2 and later between 3 and 4. Since the beam was stable on such a short time scale, this procedure ensured equal luminosities for each member of the pair.

Due to the loss of polarisation of the atoms in the target through collisions with the cell walls or through the recombination into molecules, the polarisation of the deuterium in the cell is smaller than that of the atoms coming from

Pol.	Modes 1,2			Modes 3,4		
	Ideal	Measured	Sys. err.	Ideal	Measured	Sys. err.
ΔQ_y	+2	1.46 ± 0.01	0.03	0	-0.07 ± 0.01	0.01
$\langle Q_y \rangle$	0	-0.03 ± 0.01	0.01	0	-0.02 ± 0.02	0.01
ΔQ_{yy}	0	0.17 ± 0.02	0.01	-3	-1.68 ± 0.02	0.14
$\langle Q_{yy} \rangle$	+1	0.88 ± 0.03	0.11	$-\frac{1}{2}$	-0.13 ± 0.06	0.03

Table 1

The ideal and measured polarisations of the target given in terms of average polarisations, $\langle Q \rangle$, and the polarisation differences, ΔQ , between the members of the two pairs of polarised modes used in the ANKE experiment. The systematic uncertainties, arising from the analysing powers of the proton-deuteron elastic reaction, are listed separately. It is important to note that the effective target thicknesses are identical in the (1,2) modes, as they are also in the (3,4) modes.

the ABS. The values of the target polarisations have therefore to be established under the actual conditions of the experiment and, for this purpose, elastic proton-deuteron scattering was measured, with the recoiling deuteron being detected in the STT. It is here very important to be sure that the reaction had taken place on the target gas rather than on the aluminium walls. To provide a rapid simulation of this background, the cell was later filled with unpolarised nitrogen gas. As shown in Fig. 2a, this gives a very good description of the background away from the missing-mass peaks that are associated with the unobserved proton coming from the deuterium target. In the pd elastic scattering case the background is in any case very low; there is no difficulty at all in identifying elastic events because of the strong link between the angle and the energy deposited in the STT.

Elastic proton-deuteron scattering has a high cross section at small angles and, though this varies fast with momentum transfer, this quantity is very well determined in the STT. There are measurements of both the vector A_y and tensor A_{xx} and A_{yy} analysing powers of the $\vec{dp} \rightarrow dp$ reaction with polarised deuteron beams at neighbouring energies to our 600 MeV per nucleon. The data from Argonne at $T_d = 1194$ MeV [17], from SATURNE at $T_d = 1198$ MeV [18,19], and from ANKE at $T_d = 1170$ MeV [20] show strong and well measured analysing powers.

For a two-body reaction, such as \vec{pd} elastic scattering, or a more general process, such as $\vec{pd} \rightarrow n\{pp\}_s$, where one does not consider the internal variables of the diproton, the number of particles N scattered at polar angle θ and azimuthal angle ϕ is given by

$$N(\theta, \phi) = N^0(\theta) \left\{ 1 + \frac{3}{2} Q_y A_y^d(\theta) \cos \phi + \frac{1}{4} Q_{yy} [A_{yy}(\theta)(1 + \cos 2\phi) + A_{xx}(\theta)(1 - \cos 2\phi)] \right\}, \quad (1)$$

where ϕ is measured from the horizontal plane of the COSY accelerator. Here N^0 is the corresponding number obtained with an unpolarised beam.

The STT [16], which have limited angular acceptance, are placed in the same horizontal plane as the target cell and, under these conditions, only accept events close to

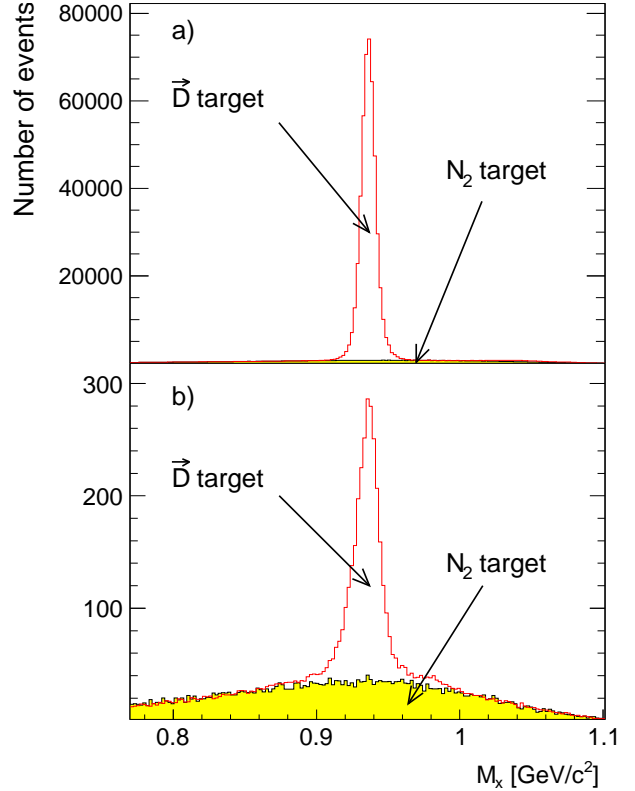


Fig. 2. The missing-mass M_X spectra of the $\vec{pd} \rightarrow dX$ (a) and $\vec{pd} \rightarrow ppX$ (b) reaction measured in the STT for 600 MeV protons incident on the polarised cell target. In both cases the shape of the background was simulated by filling the cell with unpolarised nitrogen gas.

$\phi = 0^\circ$ and 180° . As a consequence, the present measurements are primarily sensitive to the values of A_y and A_{yy} for any reaction. During the experiment the working conditions for the STT were such that the difference between the total efficiencies for different polarised modes in a pair is expected to be very small. This was experimentally verified using background events that were free from polarisation effects. Such events were collected from the vicinity of the missing-mass peak corresponding to the elastic pd scattering of Fig. 2a. By building the count ratios between the two members of a polarisation pair, which is directly the product of relative efficiency times the relative luminosity between the two modes, it was shown that the relative efficiency is unity within 1.5%. We note here again that the luminosities are the same for each of the polarisation modes in a given pair of Table 1.

Using the data from the left and right STT separately, the ratios of the difference to the sum of counts were built for each pair of polarised modes. We describe here the procedure used for modes (1,2); modes (3,4) were treated in a similar fashion. The (1,2) ratios correspond to:

$$\frac{N_1 - N_2}{N_1 + N_2} = \frac{\Delta V + \Delta T}{2(1 + \langle V \rangle + \langle T \rangle)}, \quad (2)$$

where N_1 and N_2 are the number of counts in modes 1 and 2. In terms of polarisation observables,

$$\begin{aligned}
\Delta V &= \frac{3}{2} \Delta Q_y A_y^d(\theta) \cos \phi, \\
\langle V \rangle &= \frac{3}{2} \langle Q_y \rangle A_y^d(\theta) \cos \phi, \\
\Delta T &= \frac{1}{4} \Delta Q_{yy} [A_{yy}(\theta)(1 + \cos 2\phi) + A_{xx}(\theta)(1 - \cos 2\phi)], \\
\langle T \rangle &= \frac{1}{4} \langle Q_{yy} \rangle [A_{yy}(\theta)(1 + \cos 2\phi) + A_{xx}(\theta)(1 - \cos 2\phi)],
\end{aligned} \tag{3}$$

where $\Delta Q = Q_1 - Q_2$ and $\langle Q \rangle = (Q_1 + Q_2)/2$ are, respectively, the difference and the average polarisations for the (1,2) pair. The two-dimensional (θ, ϕ) maps were built from these ratios for pd elastic scattering, which were then fitted simultaneously in both variables in order to determine all four polarisation values entering in Eq. (3).

The vector (A_y) and tensor (A_{xx}, A_{yy}) analysing powers used in the polarimetry were taken as weighted averages of the measurements already mentioned [17–20] that were carried out at very close energies per nucleon. Since Eq. (1) shows that the polarised cross section is significantly less sensitive to the tensor than the vector term, Q_{yy} is less well determined than Q_y . The results listed in Table 1 clearly illustrate this behaviour. Moreover, the systematic uncertainties, arising from the determination of the input analysing powers, are significantly larger for the tensor polarisations. Estimates for these uncertainties are also given in Table 1.

When measuring the $\vec{p}d \rightarrow \{pp\}_s n$ reaction with a polarised deuteron beam by detecting the two fast protons in the ANKE forward detector, it was possible to investigate regions where the momentum transfer q between the deuteron and the diproton and the diproton energy E_{pp} were both small [5]. This is no longer the case in inverse kinematics when the two slow protons are measured in the STT. This is due to the requirement that the protons pass through the first silicon layer of the detector. They then have energies above 2.5 MeV, i.e., momenta above about 70 MeV/c. This means that, if the two protons are measured in different STT, then q can be small but $E_{pp} \gtrsim 6$ MeV because the protons are going in opposite directions. On the other hand, if the two protons are measured in the same STT, then E_{pp} can be small but the momentum transfer has a lower limit of $q \gtrsim 2 \times 70$ MeV/c. There is therefore a significant hole in the acceptance, which is demonstrated by the data shown in Fig. 3. This is in complete contrast to the deuteron beam data, where the region where $E_{pp} < 3$ MeV and $0 < q < 140$ MeV/c is routinely accessed [5].

In this letter we report only on results obtained at low E_{pp} for events where the two protons entered the same STT. These data provide a natural continuation from the small q region studied in the deuteron beam measurements [5]. Having detected two protons in one STT the missing mass of the $\vec{p}d \rightarrow ppX$ reaction is constructed and an example of this is shown in Fig. 2b. For this three-body final state the measurement errors are larger than for pd elastic scattering and the background from the cell walls can be more problematic. However, the shape of this background is simulated very well by the contribution from the nitrogen gas filling that is also shown. Similar background subtractions

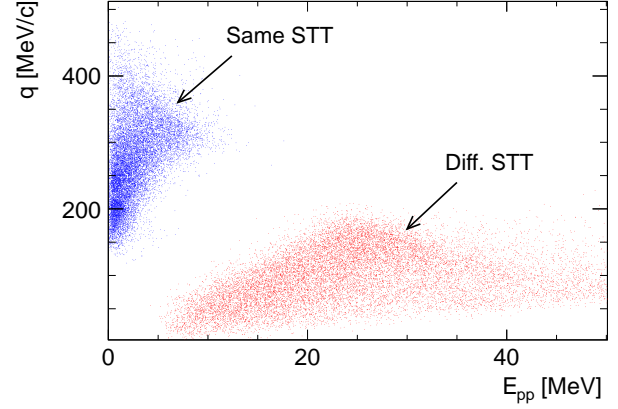


Fig. 3. The three-momentum transfer q versus the pp excitation energy E_{pp} for the $\vec{p}d \rightarrow \{pp\}_s X$ events at $T_p = 600$ MeV that fall within $\pm 3\sigma$ of the neutron peak. The data are shown separately for cases where the two protons enter the same (blue) or different (red) STT. The current construction of the STT means that there can be no events where q and E_{pp} are simultaneously small.

were made for all four polarisation modes of Table 1, where the nitrogen normalisation was fixed from fitting outside the peak region.

Data were taken by flipping the target polarisations between modes (1,2) or between (3,4). Since ΔQ_y is largest for the (1,2) pair, this combination provides the best measurement of the deuteron vector analysing power A_y^d in the charge exchange reaction, using the same technique as that employed for the polarimetry in pd elastic scattering. Corrections for the tensor analysing powers effects in the charge-exchange reaction were made using impulse approximation predictions [6]. As shown in Fig. 4, for the standard cut of $E_{pp} < 3$ MeV it was found that $A_y^d = 0$ within error bars, with an average over all momentum transfers of $\langle A_y^d \rangle = 0.005 \pm 0.008$. This agrees with theoretical predictions [1] and experimental results at lower momentum transfers [4,5].

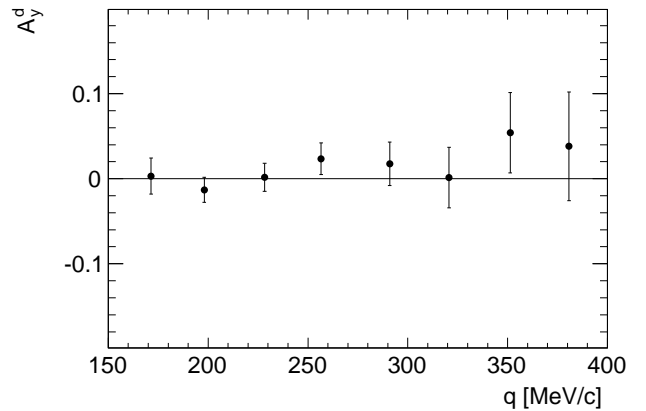


Fig. 4. Deuteron vector analysing power A_y^d of the $\vec{p}d \rightarrow n\{pp\}_s$ reaction with an $E_{pp} < 3$ MeV cut. Impulse approximation predictions [6] based upon the SP07 solution for the neutron-proton elastic scattering amplitudes [7] were used to correct for tensor analysing power effects.

The best determination of the tensor analysing power A_{yy} is found by comparing the rates in modes (3,4), which have the same luminosities but tensor polarisations of opposite sign. The results with the standard E_{pp} cut are shown in Fig. 5, where they are compared with ANKE data at lower momentum transfers [4] and also with impulse approximation predictions [6]. With the $E_{pp} < 3$ MeV cut it is believed that the 1S_0 state dominates at small q but P and higher waves become more important as q increases. A tighter cut on E_{pp} would, in principle, be possible since the E_{pp} resolution is around 0.3 MeV for $E_{pp} < 1$ MeV and below 1 MeV for higher E_{pp} . However the count rate drops rapidly with a lower E_{pp} cut and the currently available data might not help in the identification of any possible dilution of A_{yy} by the higher partial waves.

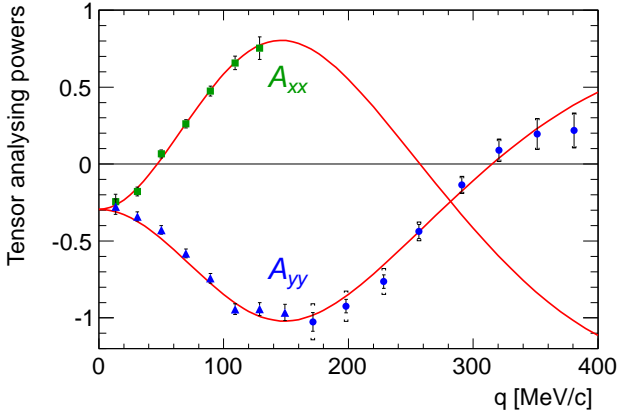


Fig. 5. Tensor analysing powers A_{xx} (green squares) and A_{yy} (blue triangles) of the $\vec{d}p \rightarrow \{pp\}_s n$ reaction with $E_{pp} < 3$ MeV from the earlier deuteron beam measurements at 600 MeV/nucleon [4]. These data were restricted to the region $q < 160$ MeV/c. The current A_{yy} results (blue dots), which provide data in the region $q > 160$ MeV/c, were obtained in inverse kinematics using a 600 MeV unpolarised proton beam incident on a polarised deuterium target. The extended error bars indicated by \square and \blacksquare , which are important in the STT data below 250 MeV/c, include the effects arising from the uncertainties in the target polarisations. The curves are impulse approximation predictions [6] based upon the SP07 solution for the neutron-proton elastic scattering amplitudes [7].

The new A_{yy} results shown in Fig. 5 are very large below about 200 MeV/c but join quite smoothly onto the lower momentum transfer data obtained with the polarised deuteron beam [4]. Furthermore the data seem to be essentially consistent with impulse approximation predictions [6]. However, at such large values of q one has to question to what extent the single scattering of impulse approximation is still quantitatively valid. Formulae have been derived that incorporate the effects of double scattering but only for the 1S_0 final state [1]. Such terms have little effect for momentum transfers below 140 MeV/c where A_{yy} has its minimum but double scattering in the 1S_0 limit tends to push the momentum transfer for which A_{yy} crosses zero down by about 20 MeV/c. On the other hand, double scattering will be far less important for P and higher waves in the pp system and so the 20 MeV/c

shift must be considered as very much an upper limit. More detailed calculations are in progress.

Data taken with two separate STT have necessarily large E_{pp} , which will generally reduce the analysing power signal through the excitation of higher partial waves [6]. Unfortunately, the data so far obtained have very limited statistics and could not usefully determine the tensor analysing power at high E_{pp} .

Measurements at higher energies are scheduled for the near future and these will also include studies with polarised proton beams in order to determine spin-correlation coefficients. After the installation of a Siberian snake at COSY, it may even be possible to study spin-longitudinal-spin-transverse correlations. Another attractive possibility is to measure in coincidence fast protons or pions in the ANKE magnetic spectrometer. These would allow one to study in detail the $\{pp\}_s \Delta^0(1232)$ final state, where the decay $\Delta^0(1232) \rightarrow \pi^- p$ defines the alignment of the isobar [8].

We are grateful to other members of the ANKE Collaboration for their help with this experiment and to the COSY crew for providing such good working conditions, especially in respect of the polarised deuterium cell. The values of the SAID neutron-proton amplitudes were kindly furnished by I.I. Strakovsky. This work has been partially supported by the Forschungszentrum Jülich COSY-FFE, the Georgian National Science Foundation, and the CSC programme #2011491103.

References

- [1] D. V. Bugg and C. Wilkin, Nucl. Phys. A **467** (1987) 575.
- [2] C. Ellegaard et al., Phys. Rev. Lett. **59** (1987) 974.
- [3] S. Kox et al., Nucl. Phys. A **556** (1993) 621.
- [4] D. Chiladze et al., Phys. Lett. B **637** (2006) 170.
- [5] D. Mchedlishvili et al., Eur. Phys. J. A **49** (2013) 49.
- [6] J. Carbonell, M. B. Barbaro, and C. Wilkin, Nucl. Phys. A **529** (1991) 653.
- [7] R.A. Arndt, W.J. Briscoe, I.I. Strakovsky, R.L. Workman, Phys. Rev. C **76** (2007) 025209; <http://gwdac.phys.gwu.edu>.
- [8] A. Kacharava, F. Rathmann, C. Wilkin, *Spin Physics from COSY to FAIR*, COSY proposal #152 (2005), arXiv:nucl-ex/0511028.
- [9] D. Mchedlishvili, S. Barsov, and C. Wilkin, COSY proposal #218 (2013), available from <http://www.collaborations.fz-juelich.de/ikp/anke>.
- [10] S. Barsov et al., Nucl. Instrum. Methods A **462** (2001) 364.
- [11] R. Maier et al., Nucl. Instrum. Methods A **390** (1997) 1.
- [12] M. Mikirtychyan et al., Nucl. Instrum. Methods A **721** (2013) 83.
- [13] K. Grigoryev et al., AIP Conf. Proc. **915** (2007) 979; K. Grigoryev et al., Nucl. Instrum. Methods A **599** (2009) 130.
- [14] K. Grigoryev et al., (*in preparation*).
- [15] R. Engels et al., Rev. Sc. Instrum. **74** (2003) 4607.
- [16] R. Schleichert et al., IEEE Trans. Nucl. Sci. **50** (2003) 301.
- [17] M. Haji-Said et al., Phys. Rev. C **36** (1987) 2010.
- [18] J. Arvieux et al., Nucl. Phys. A **431** (1984) 613.
- [19] J. Arvieux et al., Nucl. Instrum. Methods A **273** (1988) 48.
- [20] D. Chiladze et al., Phys. Rev. ST Accel. Beams **9** (2006) 050101.